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By Robert B. Spiers, Jr., and Charles Husson [1963] 23 p refs

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DEVELOPMENT OF A ROCKETBORNE SPECTRORADIOMETER

TO MEASURE THE RADIATION ENVIRONMENT

OF A REENTRY VEHICLE

By Robert B. Spiers, Jr., and Charles Husson

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ABSTRACT

A flight spectroradiometer has been developed for measuring the ultraviolet and visible spectral steradiancy of the hot-gas plasma of a supercircular velocity reentry vehicle. It has a spectral range from 2,500 angstroms to 6,000 angstroms and a dynamic range from 10^{-7} to 10^{-3} $\frac{\text{watts}}{\text{cm}^2\text{-steradian-micron}}$. The experimental parameters and vehicle characteristics affecting the spectroradiometer design is presented with a description of the optical window, spectroradiometer design, and calibration procedures. Finally, the flight performance is discussed.

DEVELOPMENT OF A ROCKETBORNE SPECTRORADIOMETER TO MEASURE THE RADIATION ENVIRONMENT OF A REENTRY VEHICLE

By Robert B. Spiers, Jr.* and Charles Husson**

INTRODUCTION

A flight spectroradiometer has been developed as a reentry payload sensor for the Langley Research Center's Five-Stage Scout Reentry Project. The purpose of the sensor is to measure the spectral and total intensity of the luminescent air in the shock-induced flow field produced by the vehicle reentering the earth's atmosphere at a velocity of approximately 28,000 feet per second. At this velocity the radiative heat transfer to a vehicle due to the luminescent air is insignificant compared to the convective heat transfer. However, the magnitude of the hot-air radiation should be great enough to detect and measure. Due to the absence of flight data of this type a radiative heat-transfer experiment was selected as one in a series of reentry experiments to be performed. There are no flight-tested spectroradiometers for use in such experiments. So the development and evaluation of a rocketborne spectroradiometer was taken as an additional objective of the radiative heat-transfer experiment.

The Scout vehicle used to perform these experiments is shown in figure 1. For the radiative heat-transfer experiment the vehicle is launched from Wallops Island, Virginia, with a trajectory as shown in figure 2. After launch the vehicle goes through a series of staging events which causes the fifth-stage payload to reenter approximately 275 nautical miles south of Bermuda. A tracking station on Bermuda and one on a ship records the reentry data in real time and delayed time. The delayed-time data are provided by an onboard tape recorder in case radio blackout is experienced during the prime data period. A telemeter transmitter in the fifth-stage payload transmits the data to the tracking stations. The payload shown in figure 3 has a beryllium nose with an optical window on its axis to transfer the radiant energy to the spectroradiometer sensor. There the quantities to be measured are converted into electric signals and fed into the telemetry module for transmission to the tracking stations. The 17-inch-diameter spherical rocket motor boosts the payload to its final reentry velocity. No attempt is made to recover the payload.

The nose window and spectroradiometer part of the fifth stage is discussed in this paper. Their final design and construction resulted from factors peculiar to the radiative heat-transfer experiment and the rocket vehicle used.

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DESIGN CONSIDERATIONS

Experimental

As stated before, the experimental quantities to be measured are the spectral and total intensity of the shock-induced flow-field radiation. An analysis of the expected hot-air radiation was made in order to determine the required sensor range, sensitivity, frequency response, and resolution. The analysis was made using a theory of hot-air radiation (ref. 1) which was derived from laboratory measurements. This theory gives sufficient indications of the spectral emission of gases at the temperatures and densities of interest. The expected flow-field gas temperatures and densities were taken from normal shock data (ref. 2) which applies to the hypervelocity reentry trajectory. An altitude versus velocity curve for the experiment is shown in figure 4. Radiation from hot air in the altitude range from 350,000 feet to 150,000 feet was taken as the region of primary interest. Calculations of the spectral radiation from several of the most intense air constituents were made for the various temperatures and densities throughout this altitude range. One set of spectra is shown in figure 5 for an intermediate altitude. The peaks and inflections in the upper curve indicate the spectral features due to the ionized nitrogen molecule's first negative band system. The lower curves are due to two nitric oxide, NO, band systems. The expected dynamic range of radiant energies is shown in figure 6. This curve shows the change in specific intensity, or steradiancy, over the reentry period for the 3,900-angstrom radiation of the $N_2^+(1-)$ band system. The steradiancy increases by approximately 7 decades during a 25-second data period. This analysis of the flow-field radiation suggests the following sensor design characteristics. The sensor should provide a spectrum over the wavelength range from 2,000 to 6,000 angstroms and a total radiation measurement over as wide a wavelength range as the window transmits. The spectral part of the sensor should have a resolution of 75 angstroms to resolve the expected molecular band spectra. It should record the spectrum in approximately 1/5 of a second if a spectrum is to be obtained which does not change in intensity significantly during the scan. It should be able to detect a minimum steradiancy of $10^{-6} \dfrac{\text{watt}}{\text{cm}^2\text{-steradian-micron}}$ and have a dynamic range covering 7 decades of radiant energy. In addition to these characteristics the vehicle configuration suggests the sensor be packaged in a cylindrical volume no larger than 10 inches in diameter and 6 inches deep. It should not weigh more than 10 pounds.

Environmental

The environment in which the sensor must operate also affects its design. The maximum vibrations and accelerations are listed in table I. The temperature will vary from 75° to 130° F and the pressure will vary from 1 atmosphere to the vacuum of space. During the period of reentry the optical window must efficiently transfer the radiation to the spectroradiometer while being subjected to a peak heat pulse of 800 Btu/ft^2-sec.

DESCRIPTION OF SENSOR

General

A sketch of the sensor designed to meet the above requirement is shown in figure 7. It consists of a vehicle nose window, an optical monochromator, a thermistor system, and a photoelectric system. These components are combined into one unit that forms the nose section of the fifth-stage rocket.

The hot-gas radiation in the stagnation-point region of the nose passes through a fused quartz window, the internal surface of which is used as the entrance slit of a modified Ebert type scanning monochromator (ref. 3). The radiation passes through the monochromator as shown forming a spectrum at the exit slit. The spectrum is scanned across the exit slit by oscillating the diffraction grating with an electric motor. The narrow spectral band of radiation that passes through the exit slit excites the phototube which provides a voltage output to one channel of the telemetry system. Part of the radiation passing through the nose window illuminates the total radiation thermistor detector. This radiation is chopped by a motor-driven squirrel-cage chopper. The total range of wavelengths that is transmitted by the window excites the detector which supplies a voltage output to another channel of the telemetry system.

Nose Window

The nose window is a fused quartz light pipe 0.020 inch wide, 0.75 inch high, and 2 inches thick. It is heat sink immersed in a beryllium nose. It is so designed to survive the extreme heat generated at the nose and to efficiently transfer radiation to the scanning monochromator and thermistor. It transmits radiation from 2,000 angstroms to 30,000 angstroms, has a melting point higher than that of beryllium, and excellent thermal shock characteristics. The 0.020-inch width of the window serves as the entrance slit width of the monochromator.

Scanning Monochromator

The scanning monochromator has an f/3.3 spherical concave collimating mirror. The plane reflection diffraction grating has 600 grooves per millimeter and is blazed for the 3,000-angstrom wavelength. The grating is oscillated sinusoidally by a 28-volt d-c electric motor. The grating oscillates at 2.5 cycles per second causing the spectrum to scan across the 0.020-inch exit slit 5 times per second. The halfpeak band width of the radiation that passes through the exit slit to the photodetector is 75 angstroms wide.

Photomultiplier Detection System

The photoelectric detector used to record the spectral radiation is a photomultiplier type 1P28. The electronics used is designed to cover approximately 5 decades of radiant energy. This essentially covers the sensitivity range of the 1P28 from a so-called "wide open" gain condition to maximum attenuation. The gain or attenuation of the photomultiplier is achieved by electronic feedback control of the high voltage applied to the photomultiplier. This is a technique employed in conventional devices to achieve a logarithmic energy response with the photomultiplier. However, all functions are achieved with solid-state devices. A block diagram of the photomultiplier system is shown in figure 8(a). The amplifier fed by the 1P28 controls the amplitude of the high voltage applied to the 1P28. In this manner optimum operating points for the photomultiplier and amplifier may be chosen. At zero signal condition, 1,000 volts are applied to the photomultiplier and the applied voltage is related to the energy level of the radiation input. The output is recorded by monitoring the high voltage through a voltage divider.

Thermistor Detection System

The thermistor detector is essentially a photoresistive bridge device. Adequate compression of the output signal, which covers 5 decades of radiant energy, is achieved by utilizing saturating operational amplifiers. Five operational amplifiers are cascaded and their outputs are divided by 10 to reduce the voltage and are then summed. Logarithmic compression is achieved by permitting each stage to saturate at an equivalent decade of energy. The last stage saturates at an input of 0.0001 volt and the first stage saturates at an input of 1 volt, indicating all states are saturated. Saturated output for each stage is 10 volts. Dividing by 10 and summing each stage, the maximum output for maximum input is 5 volts. This system was developed as an all-solid-state device. A block diagram of the system is shown in figure 8(b).

Final Configuration

The spectroradiometer-nose assembly is shown in an assembled and exploded view in figure 9. The spectroradiometer is housed in an airtight can which is purged with dry nitrogen to approximately 20-pounds-per-square-inch pressure to eliminate any low-pressure problems that might occur in the vacuum of space. All metal parts are anodized or painted black to eliminate as much stray light as possible. Lightweight metals such as aluminum and magnesium are used where possible to cut down on the weight of the instrument. The final weight of the spectroradiometer is 10 pounds. It is housed in a can 7 inches in diameter and 6 inches deep. The electrical requirements to operate the spectroradiometer are 28 volts, 250 milliamps, d-c.

SENSOR CALIBRATION

Calibration Apparatus

The spectroradiometer is calibrated with an NBS Standard of Spectral Radiance (ref. 4). This is a ribbon filament tungsten lamp which operates at

6 volts and 35 amperes and is calibrated for spectral steradiancy over the wavelength range from 2,500 angstroms to 26,000 angstroms. Neutral density filters of the wire screen type and the partially aluminized quartz type are used to attenuate the standard lamp by known amounts. The spectral transmission of these neutral density filters was measured with a spectrophotometer over the wavelength range. The spectral calibration apparatus is shown in figure 10.

Energy

Figure 11 shows the calibration curve for the spectroradiometer. The voltage output versus radiant energy input is shown for three different wavelengths of radiation. There is a change in calibration with wavelength due to nonlinear spectral response of the spectroradiometer. The minimum energy detectable for the spectral detector is approximately $10^{-7} \frac{\text{watt}}{\text{cm}^2\text{-steradian-micron}}$. The 0-5 volt output represents approximately 4 decades of radiant energy input. The total radiation thermistor detects a minimum energy of approximately $10^{-3} \frac{\text{watt}}{\text{cm}^2\text{-steradian}}$. Due to the less sensitive thermistor which has no radiation-collecting optics, the total radiation detector does not begin to record radiation until the photomultiplier saturates. The thermistor was calibrated using the same NBS standard by integrating the energy under the spectral steradiancy curve from 2,500 angstroms to 30,000 angstroms.

Wavelength

The wavelength calibration is made for the spectroradiometer by recording a spectrum of a mercury discharge lamp. A spectrum of the mercury lines is shown in figure 12 as recorded by the spectroradiometer during a rocket prelaunch system check while on the launching pad. This record shows a forward and reverse scan of the mercury spectrum. The square waves are voltage calibrate pulses at the red end of each spectral scan. The saw-toothed pulse shown by the dotted line is a radiant energy calibrate pulse generated by flashing a small tungsten lamp momentarily at the ultraviolet end of the spectral scan. The voltage and energy calibrate pulses serve to check the integrity of the system during flight. The dotted line shows the zero radiant energy input to the spectroradiometer. The approximately 0.2-volt level is due to instrument noise. The shark fin appearance of the intense 2,537-angstrom line is due to insufficient frequency response of the system. A radio-frequency filter was added late in the program to eliminate radio-frequency noise in the sensor. This, unfortunately, reduced the sensor frequency response causing the erroneous wave form.

FLIGHT PERFORMANCE

The flight spectroradiometer was launched in the night on the morning of August 23, 1962. The vehicle's third stage malfunctioned causing the fifth-stage payload to go into a flat spinning attitude. Consequently, it reentered the earth's atmosphere at a velocity much lower than predicted. Although the radiative heat-transfer-measurement objectives of the experiment were not obtained, the flight evaluation of the spectroradiometer was quite successful. Telemetry records indicate that the spectroradiometer operated properly throughout the flight. The velocity of reentry was not determined but an analysis of the flight records showed the velocity could not have been greater than 10,000 feet per second. Therefore, the probable 2,000° to 3,000° K hot-air radiation could not have been detected with the onboard spectroradiometer. Nevertheless, the ablation of vehicle materials did provide radiation the sensor could detect. One hundred and eighty-one scans of spectral radiation were measured during a 31-second period. One such recorded spectrum is shown in figure 13. This spectrum came from a hydrocarbon flame. Most likely it came from a charring ablator material (refrasil) used on part of the beryllium nose. An oxyacetylene flame spectrum is shown with the flight record to show the similarity. The peaks recorded are the carbon, C_2 Swan, band system and the CH molecular band system. The relative intensities of the two band systems are different for the two records and are due to the different modes of excitation.

CONCLUSIONS

The flight spectroradiometer sensor performed as expected, recording the radiations it detected with good fidelity. Not all the design characteristics strived for in the sensor development were obtained. The spectral resolution was finally 100 angstroms instead of 75 angstroms due to the reduced frequency response. Although the sensor could detect a wavelength range from 2,000 to 6,000 angstroms, the energy calibration below 2,500 angstroms was very poor due to insufficient radiation standards below 2,500 angstroms. The final dynamic range of the sensor covered 4 decades of radiant energy instead of 5. Due to the rocket malfunction the nose-window design was not tested. The window survival problem for hypervelocity reentry radiative transfer measurements is very difficult to solve because no ground facilities are available to reproduce the heating rates that occur during reentry. There was hope this flight would provide window survival data for use on future reentry experiments.

The final accuracy in measuring wavelength and radiant energy is as expected. Wavelength can be measured to ±50 angstroms on a final record. The radiant energy measurements have an uncertainty due to several instrument errors. The calibration standard lamp has a maximum uncertainty of ±5 percent. The spectroradiometer sensor calibration procedure results in a maximum uncertainty of ±25 percent. Another error in measuring the voltage output of the spectroradiometer through the telemetry system is ±2 percent of the full-scale reading. The maximum overall uncertainty in measuring the hot-gas steradiancy from a telemetry record is approximately ±35 percent.

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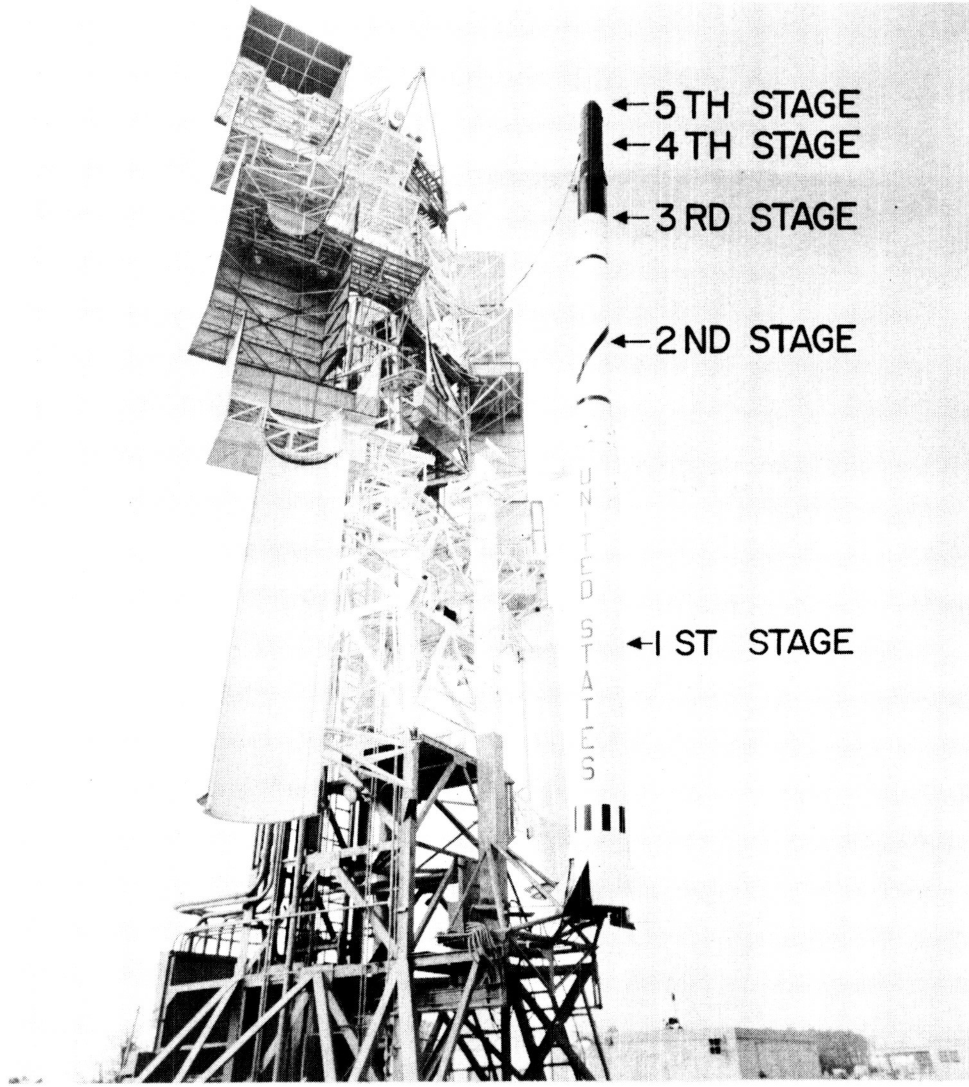

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Figure 1.- Five-stage scout rocket.

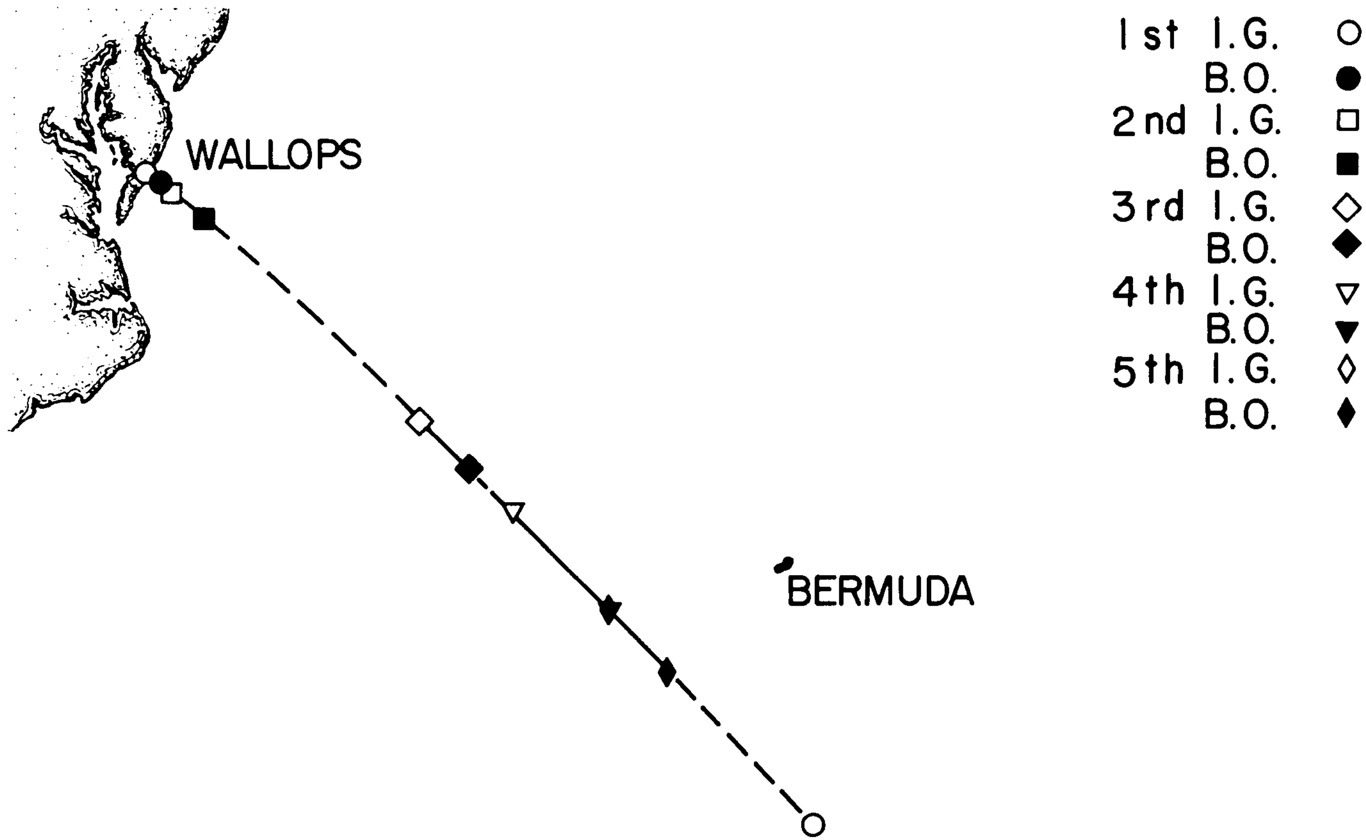

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Figure 2.- Trajectory for the reentry radiative heat-transfer experiment.

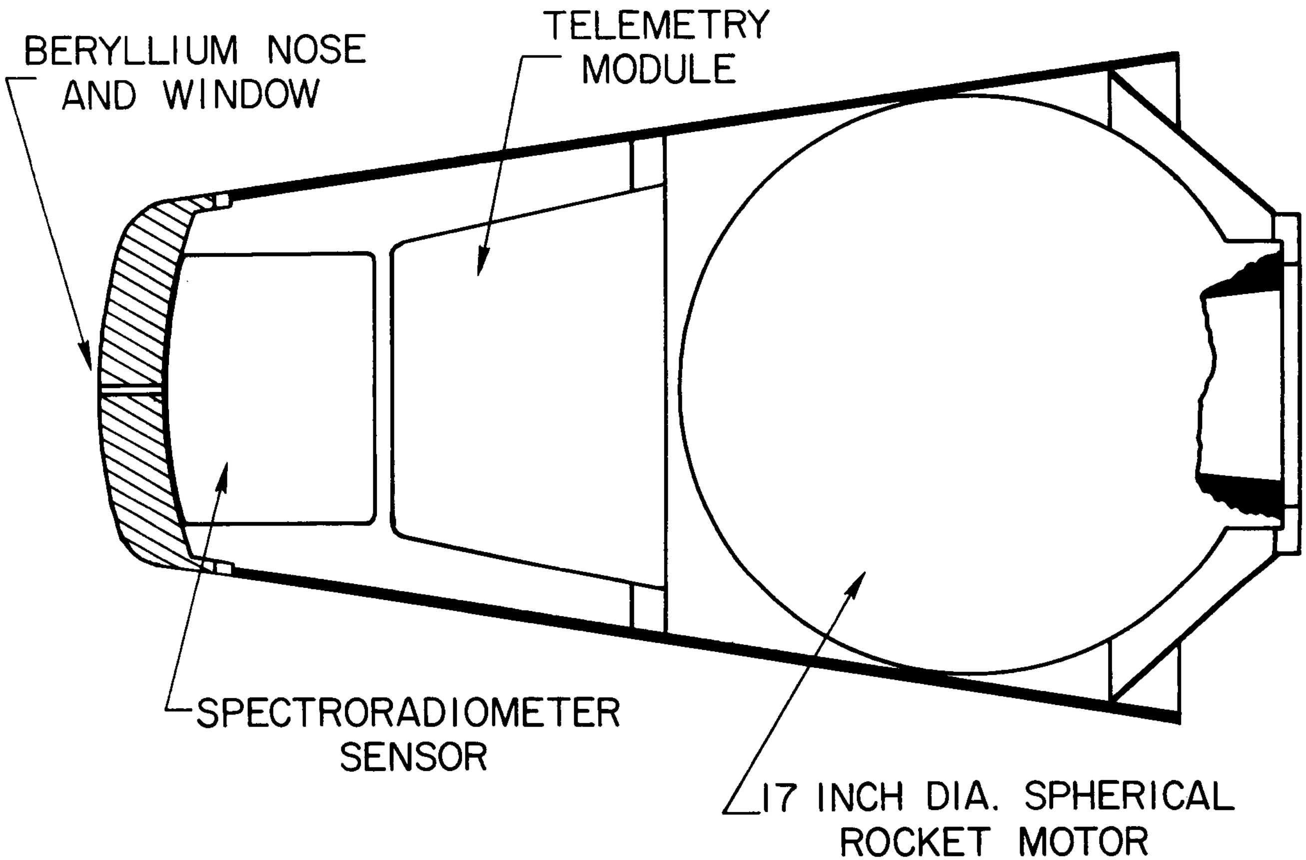

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Figure 3.- Scout fifth-stage payload.

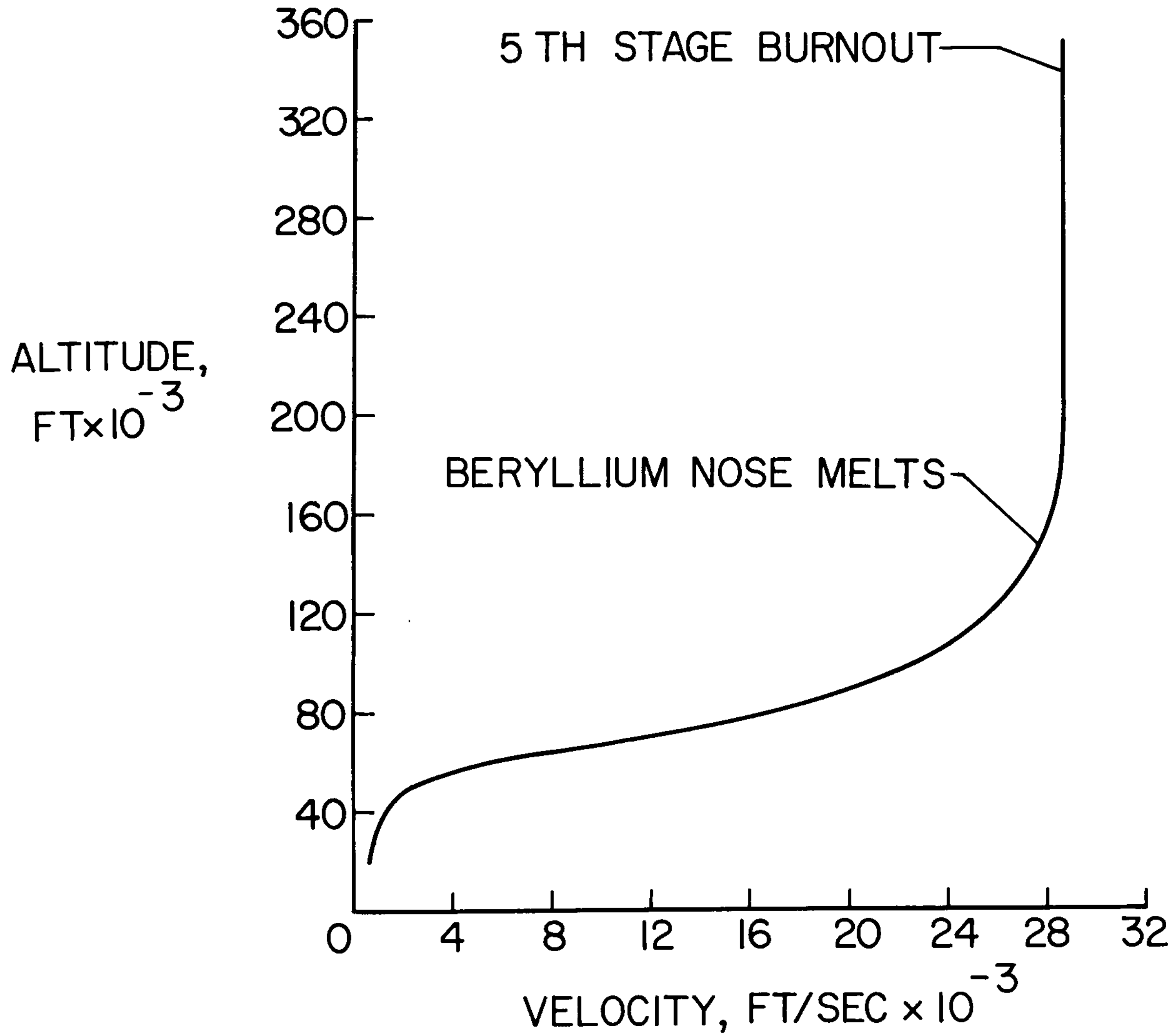

Figure 4.- Altitude versus velocity.

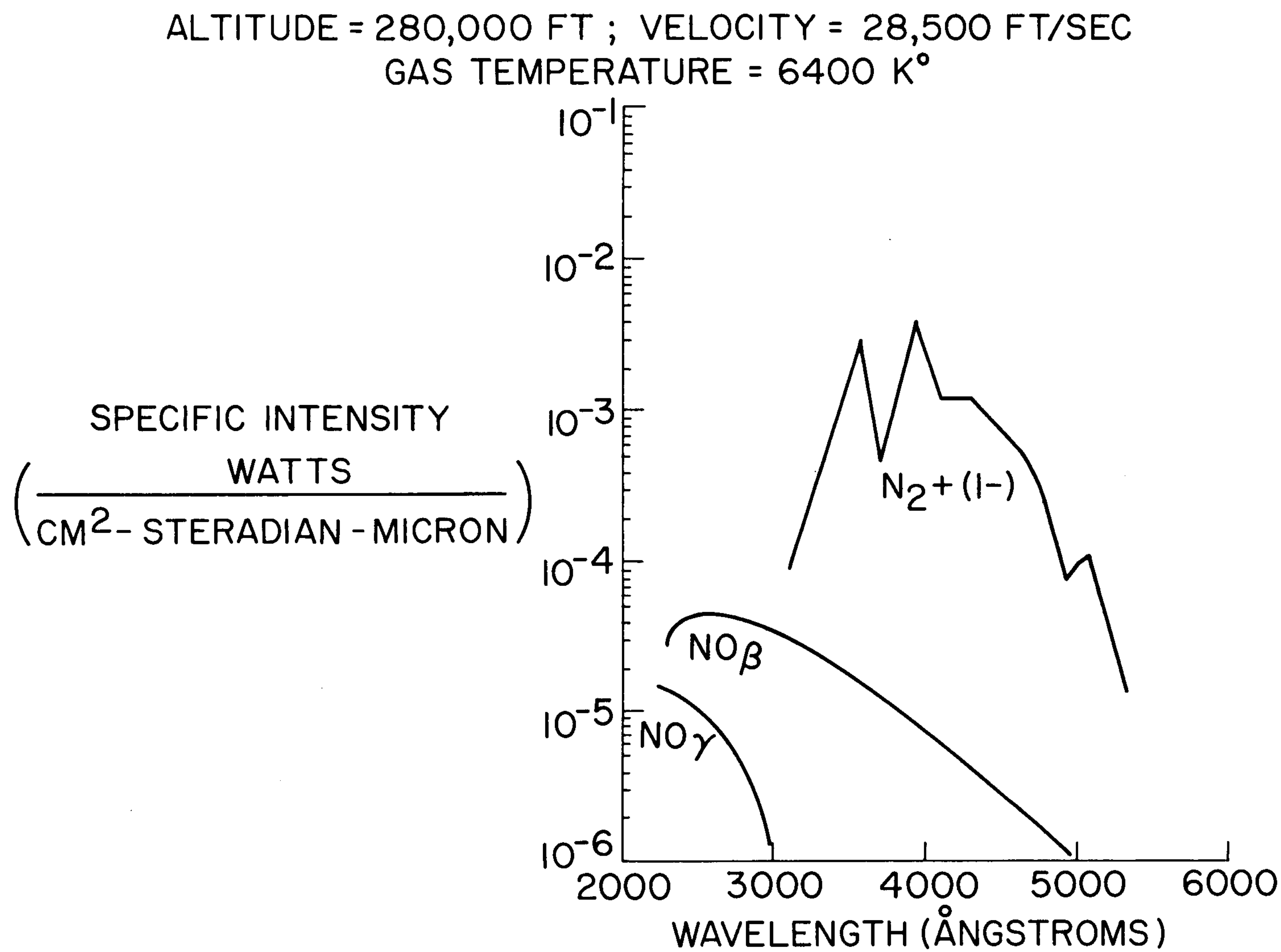

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Figure 5.- Specific intensity versus wavelength.

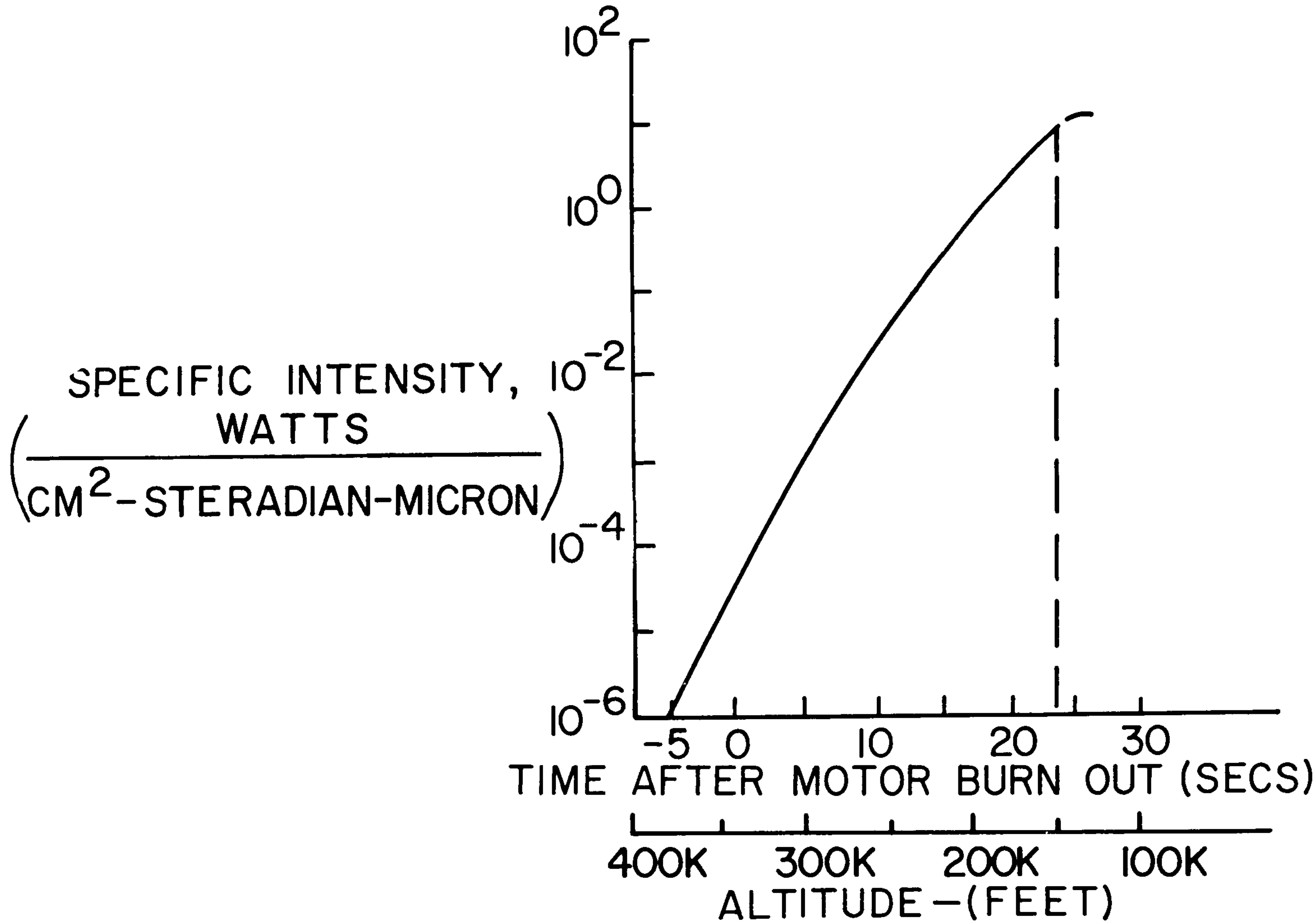

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Figure 6.- Specific intensity versus time and altitude.

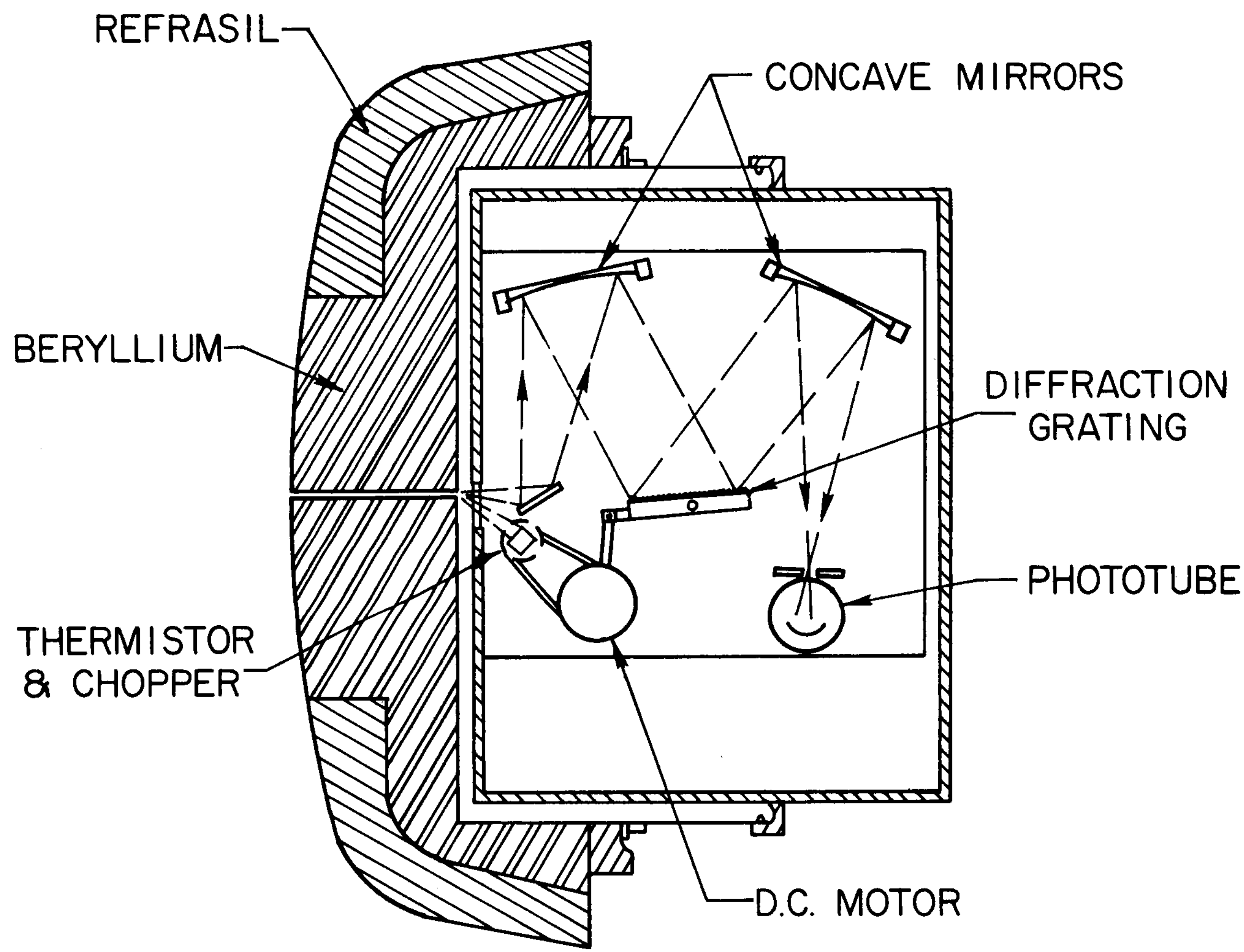

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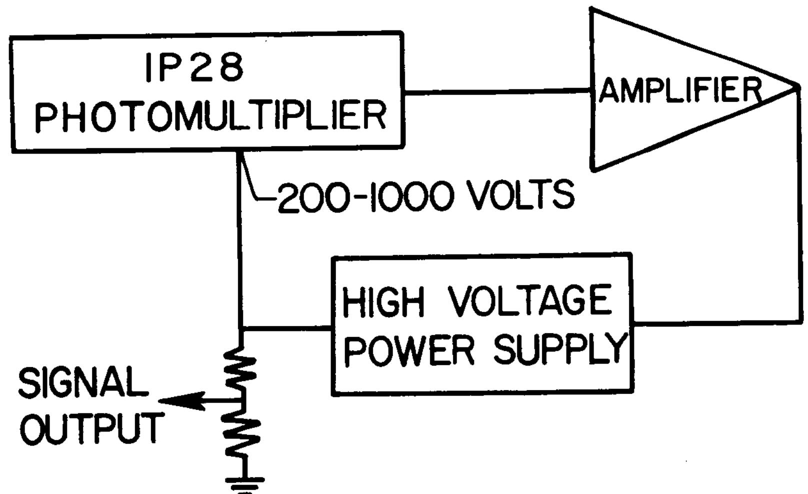
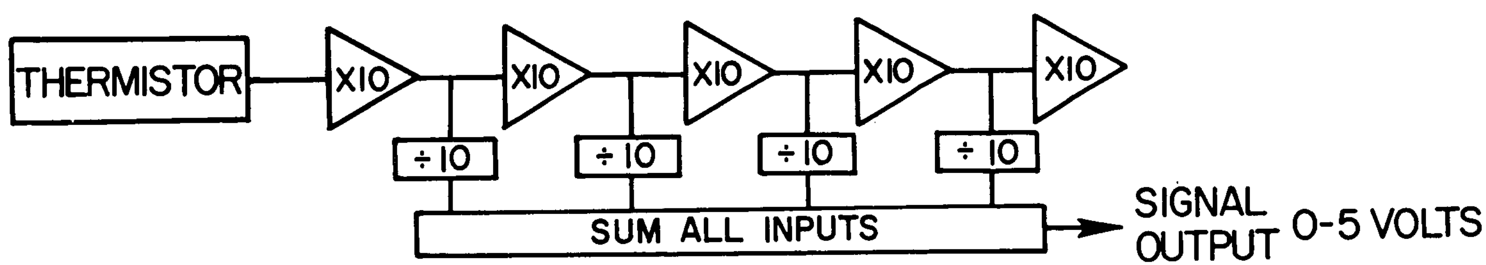
Figure 7.- Nose-sensor assembly.



(a) PHOTOMULTIPLIER SYSTEM



(b) THERMISTOR SYSTEM

NASA

Figure 8.- Detector electronics.

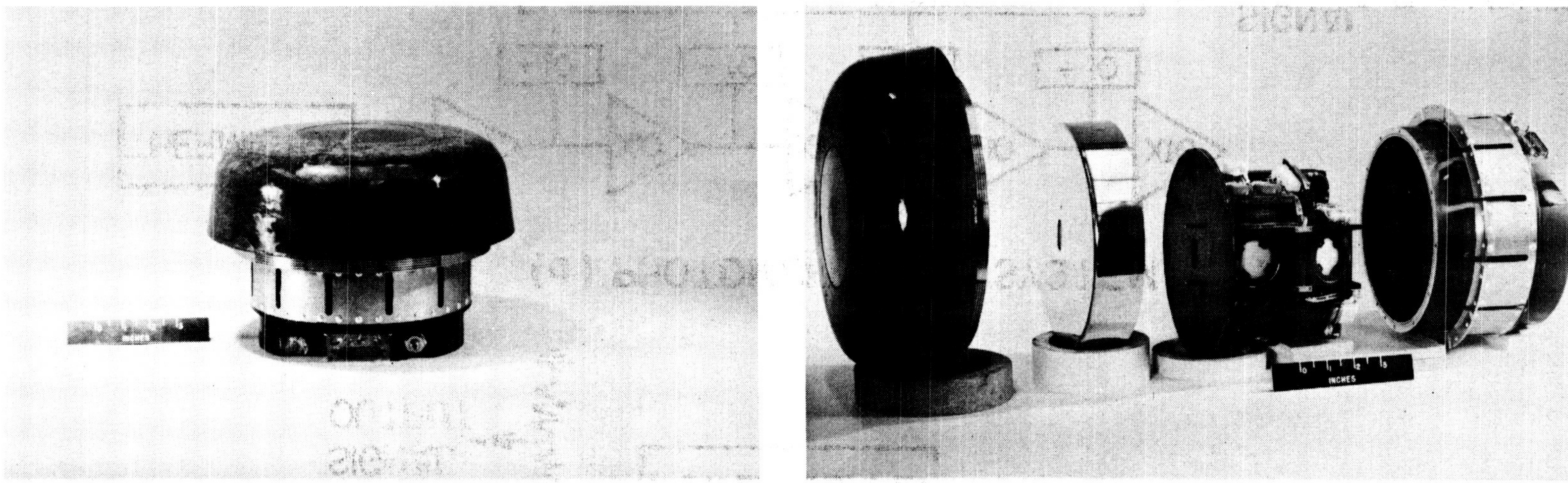


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Figure 9.- Flight spectroradiometer.

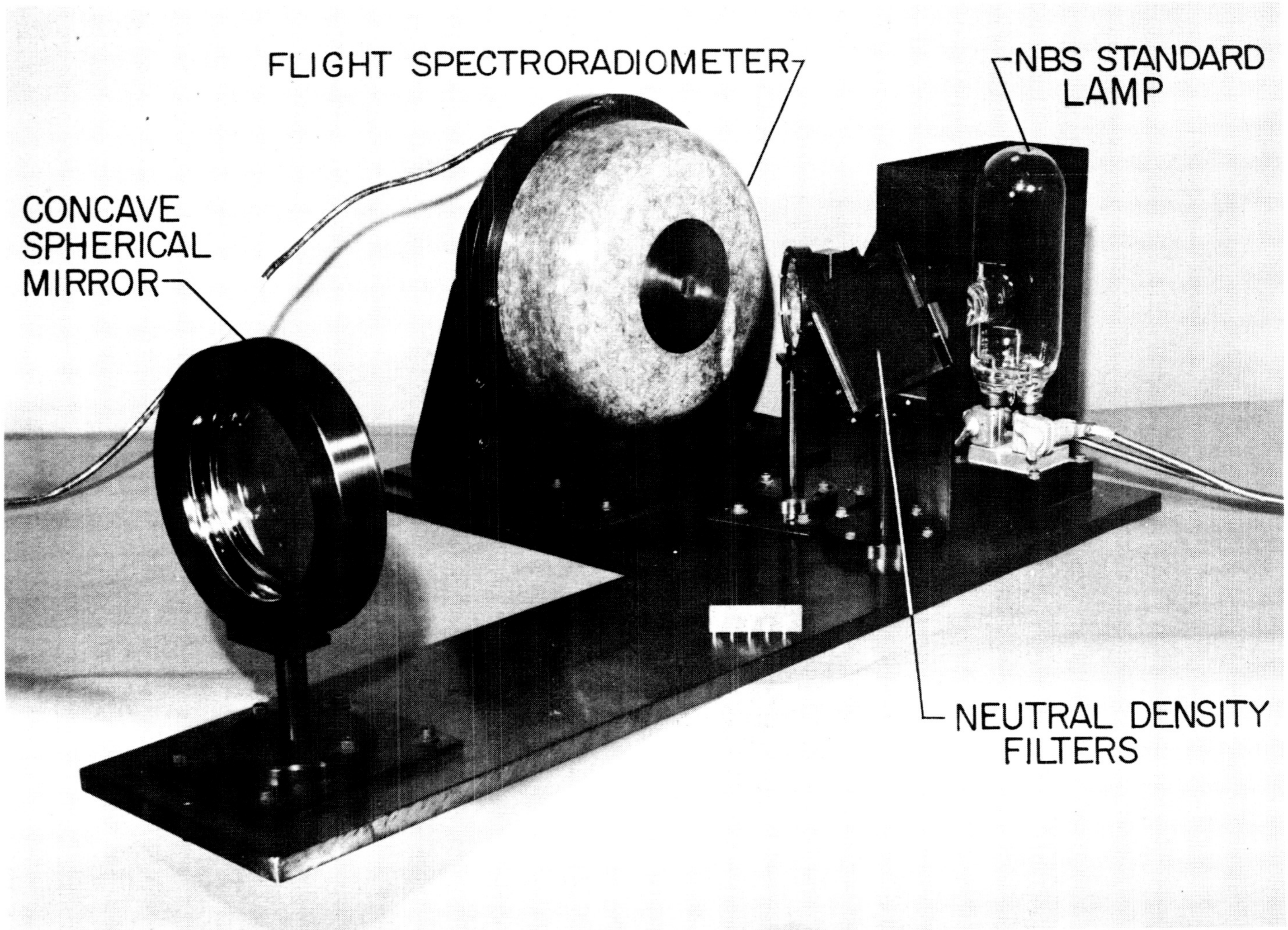

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Figure 10.- Calibration apparatus.

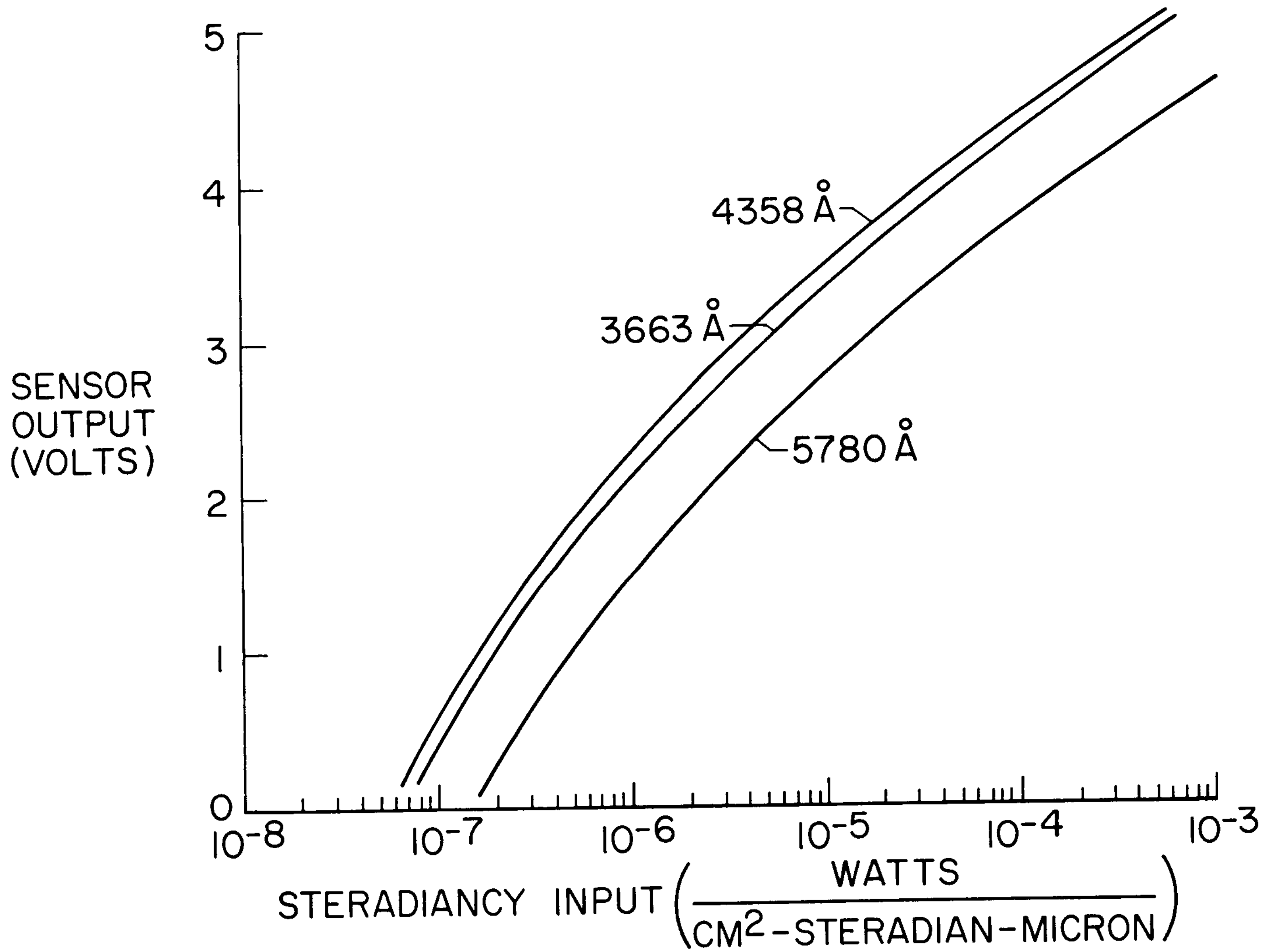

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Figure 11.- Spectroradiometer calibration curve.

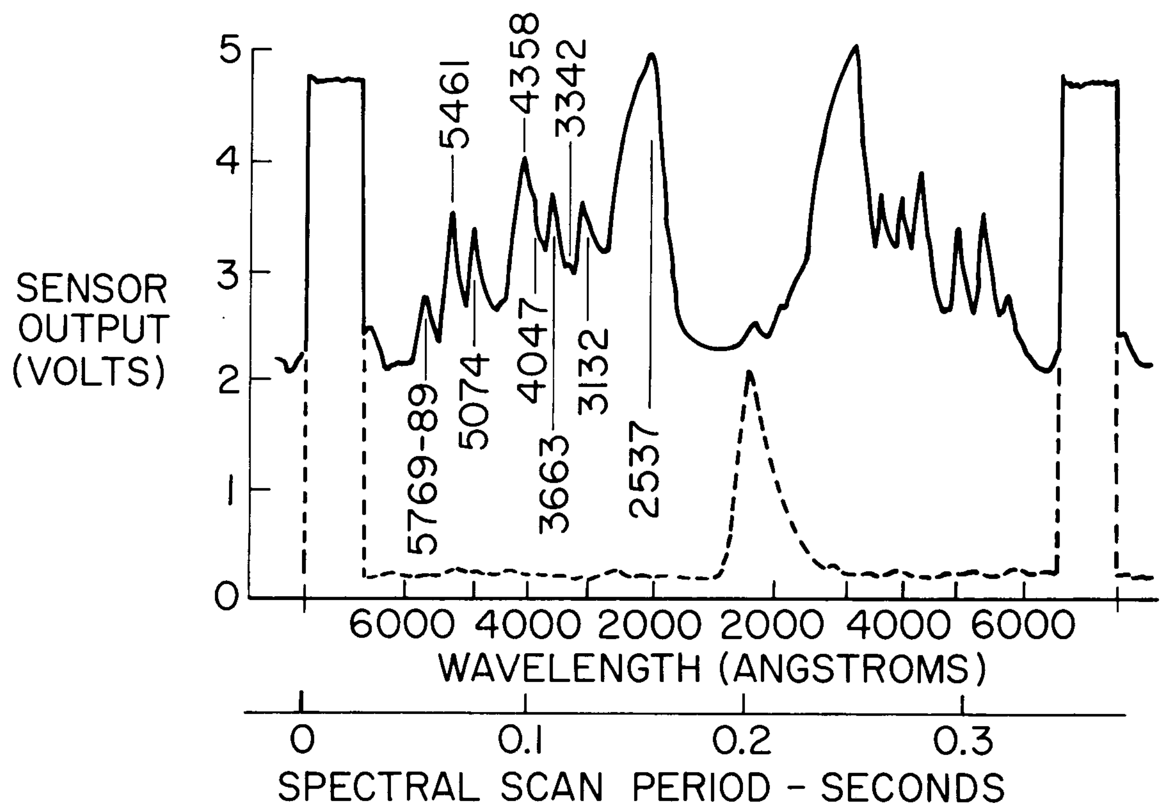

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Figure 12.- Hg spectrum as recorded by the spectroradiometer.

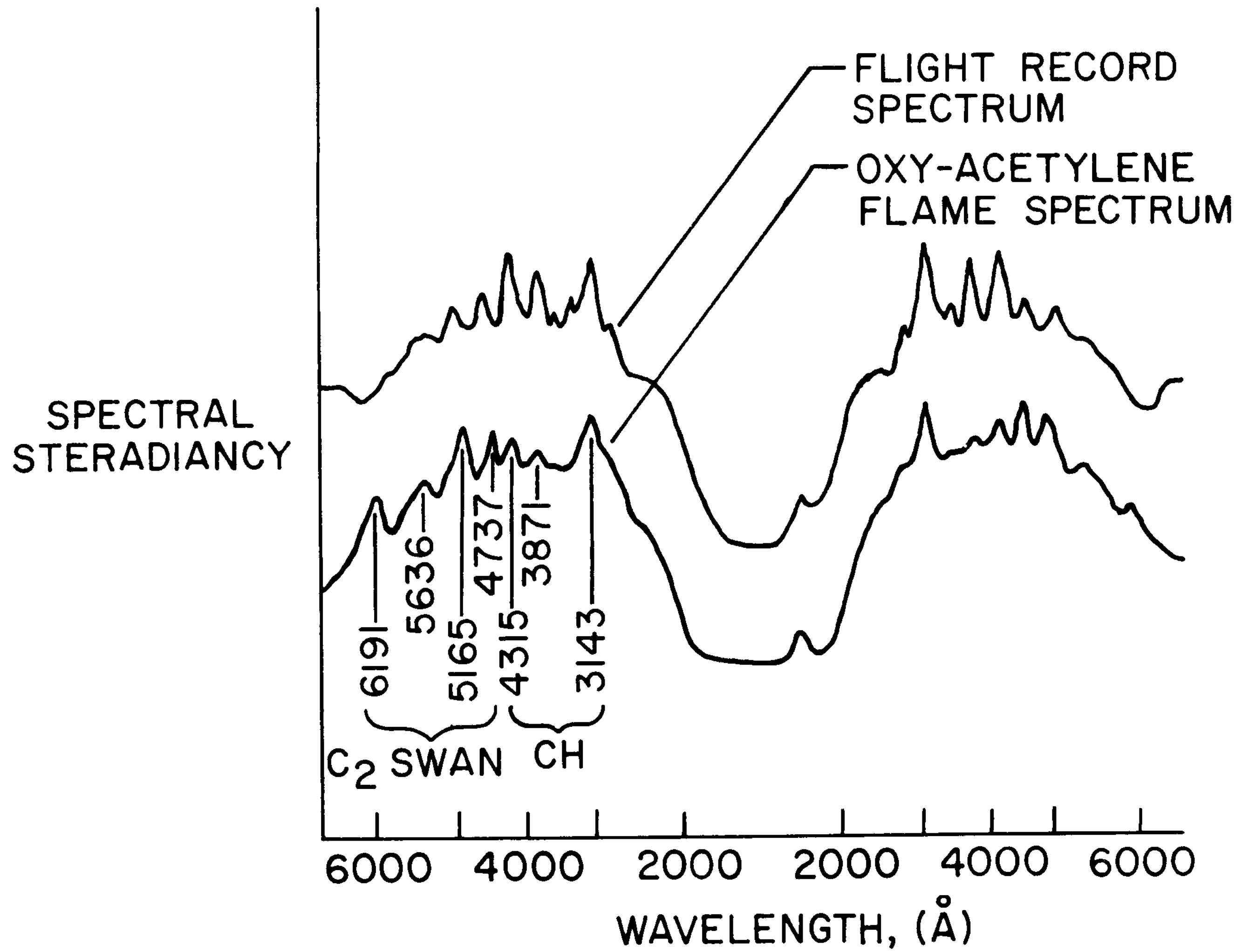

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Figure 13.- Comparison of a flight record spectrum with an oxy-acetylene flame spectrum. (Two adjacent scans of the same spectrum is shown.)

MAXIMUM LEVELS

TYPE	LEVEL	FREQUENCY	DURATION	DIRECTION
VIBRATION 1. SINUSOIDAL 2. RANDOM	9 G rms 8 1/2 G rms	500-2000 CPS 15-2000 CPS	105 SECS 110 SECS	LONGITUDINAL LONGITUDINAL
ACCELERATION (STEADY STATE)	60 G 6 G		3 MIN 3 MIN	LONGITUDINAL TRANSVERSE
SHOCK	22 G		5-15 MSECS	LONGITUDINAL

NASA

Figure 14.- Environmental test.

NASA-Langley, 1963